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Closed letter counters impair recognition

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ABSTRACT

An often-repeated piece of advice when choosing fonts for great legibility is to use fonts with large counters and apertures. To identify effects of open and closed apertures on the letters 'a', 'c', 'e', 'r', 's', 't' and 'f', we ran an experiment using the serif font Pyke as stimulus. The letters in focus were designed for this experiment with three variations of open apertures (Open, Medium and Closed). The experimental paradigm was to present a letter either with or without flankers in the parafovea at 2° eccentricity. The findings showed that participants had more trouble identifying the letter if it was set in a font variation with closed apertures.

1. Introduction

A large share of everyday reading happens while the reader is on the move, including reading on mobile devices (Chen and Lin, 2016), reading road signs (Garvey et al., 2016), reading vehicle displays (Reimer et al., 2014), and navigating complex wayfinding systems (Bosch and Gharaveis, 2017; Shi et al., 2020). Despite this, many traditions within typography originate from a time when most reading materials were books or posters. In recent years, this insufficient understanding of typographic aspects of glance-like reading has led to an increased interest in investigating how font style can influence rapid identification of letters and words (Beier and Oderkerk, 2019b; Dobres et al., 2016; Sawyer et al., 2020).

There is an often-repeated tenet in the design community that open letter counters (i.e., the entirely or partially enclosed area within a letter) are essential for font legibility (Moss, 2015; Silvertant, 2017; Suzuki, 2004). The argument is that if the letter counters are not visible enough, the ink area of the individual letter will seem perceptually to invade the internal white space and thereby increase misreading for other similar letters (Beier, 2012). Maintaining the white internal area is hence essential for letter differentiation and identification. One way of opening the counters of the letters 'c', 'e', 's', 'r', 't', 'f', and 'a' is to design these characters with open apertures (i.e., the openness between the stroke terminations of an open counter; Fig. 1). We hypothesise that closed apertures will cause a negative impact on performances and investigate effects on letter identification.

1.1. Letter feature identification

The Gestalt law of closure (Wertheimer, 1938) asserts that the perceptual system tends to fill in visual gaps of incomplete shapes and that the smaller the amount of space removed from the complete shape, the easier it is to perceive the full shape (Kim et al., 2019). A classic example is a round outline shape with a gap, which we still recognise as a full circle (Hörhan and Eidenberger, 2020). In letters such as 'c', 'e', 'a', and 's', the size of the aperture equals the gap in an otherwise closed shape. This focus on stroke termination is further supported by empirical studies investigating which part of letters mediate letter identification (Fiset et al., 2008). By performing multiple linear regressions on different parts of stimuli letters from the font Arial, the researchers found that both stroke terminations and horizontal strokes are important for letter recognition. As stroke terminations define the size of the aperture, such results support the notion that aperture design could potentially make a difference to letter recognition.

1.2. Prior experiments into effects of letter apertures

The prolific 20th-century legibility researcher Miles A. Tinker drew on his own as well as other, earlier research experiments when he stated that 'Other things being equal, the greater the enclosed white space of a letter, the greater the legibility' (Tinker, 1964, p. 36). The experiments underpinning Tinker's conclusion all involved comparisons of different font styles. The problem with such an approach is the difficulties that follow from trying to identify the effect of a specific typographical variable when the variable is not isolated in the investigation (Beier,

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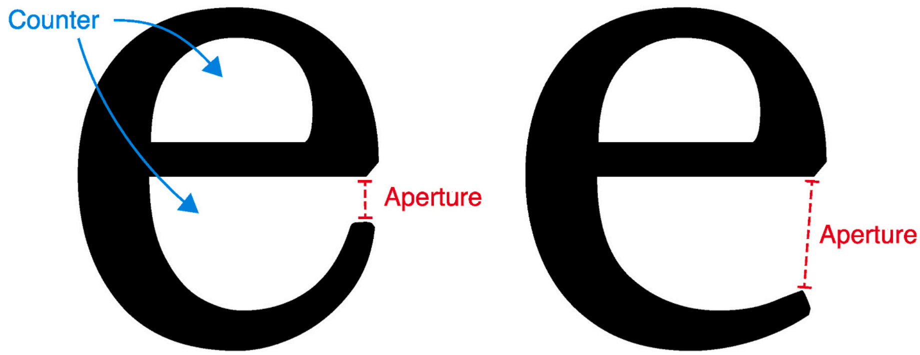

Fig. 1. Visualisation of closed aperture (left) and open aperture (right). Counters are the enclosed space within the letter.

2016; Beier and Oderkerk, 2019a). More recent studies take this into account.

Beier and Larson (2010) created and tested several letter variations within three different font styles, aiming at investigating the effect of different letter skeletons. Using a single-letter presentation paradigm, the experiment included different versions of open and closed apertures of the letters ‘c’ and ‘e’ and showed significantly lower letter recognition of closed apertures at both short exposure and great reading distances. However, since the size of the aperture was not the main research question, the remaining letters with apertures were not tested with different aperture styles.

In an experiment with numeral recognition (Beier et al., 2018), with the methodology of identifying a rapid peripheral presentation of all numerals within a three-digit string, the test material consisted of several different designs of each of the numbers within a single font style. The digits ‘2’, ‘3’, and ‘9’ all included versions that had either open or closed apertures. For the digits ‘3’ and ‘9’, the results showed evidence supporting the hypothesis that closed apertures adversely impacted performances and found that in a measure of perimetric complexity (the square of the inside and outside perimeters of a character divided by the ‘ink’ area; Pelli et al., 2006), the error rates in letter identification of the three-digit string increased with font complexity. As complexity was greater for numbers/characters with closed apertures than with open apertures, complexity levels might also impact how easy it is to identify a character of different aperture styles.

These studies investigated recognition of individual letters and digits. However, since professional fonts are built within modular systems, where all characters with apertures have the same style of openness, the present experiment studies the combined effect on the letter group.

1.3. Visual crowding

The phenomenon of visual crowding is known to result in perceptual interference from neighbouring letters (Marzouki and Grainger, 2014) as well as from the mistaken integration of neighbouring features belonging to the target (Coates et al., 2019). It is found in peripheral vision and in foveal vision both at small visual angles (Coates et al., 2018) and at short presentation times (Lev et al., 2014). It is further understood as a significant sensory factor limiting the number of letters that can be recognised at a glance in the visual eccentricity (visual span; He and Legge, 2017). As a small visual span results in low reading speed (Legge et al., 2007), this suggests that were we to reduce the influence of crowding, we could potentially improve reading in multiple scenarios.

We speculate that by increasing the size of the counters through open apertures, we will improve individual letter recognition and thus minimise interferences of neighbouring letter and feature migration.

By measuring letter recognition we will investigate 1) whether the group of seven aperture letters of the lowercase alphabet are affected by aperture size, 2) whether visual crowding can be minimised through large apertures, and 3) whether the three levels of aperture sizes tested in our experiment are significantly different from each other.

Fig. 2. From the top: the fonts Pyke Closed, Pyke Medium, and Pyke Open, the three font conditions superimposed, and, at the bottom, the remaining letters not under investigation (being the same across test fonts).

2. Experiment

2.1. Stimuli

We used the font Pyke Text Regular, a serif font with contrast between the thickest and thinnest parts of the letters. We chose this font because we have permission to alter it and because it is a relatively conservative serif-style font. Further, the round letters ‘a’, ‘c’, ‘e’, ‘f’, and ‘r’ have a teardrop shape at the top ending, and in the letters ‘e’ and ‘c’, the bottom stroke ending is relatively thin (Fig. 2). The three letter variations were designed with a gradual increase in the apertures’ degree of openness.

2.2. Participants

There were a total of 21 participants ranging in age from 20 to 39 years (M_{age} = 27.19 years, SD = 5.64 years, 10 women). Participants all self-reported normal or corrected to normal vision. Participants were

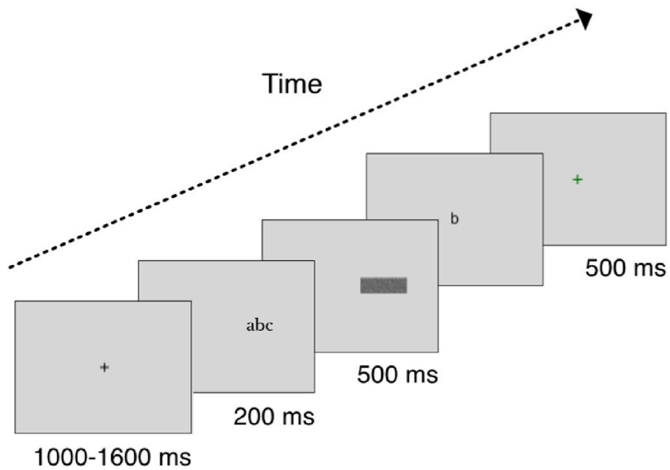

Fig. 3. Description of the experimental protocol. First, a single letter or a string of three letters was presented, then a backward mask consisting of a rectangular noise patch.

recruited through a recruitment website (Forsoegsperson.dk), and all received a gift card of DKK 300 for their participation. The data from three participants was excluded from analyses as they were unable to finish the experimental testing session due to a programming error. All participants signed a written consent form upon oral and written explanation of the experiment. The research followed the tenets of the Declaration of Helsinki and The Danish Code of Conduct for Research Integrity.

2.3. Apparatus and procedure

Stimuli were displayed on a backlit 17-inch IBM/Sony CRT monitor (refresh rate = 85hz, resolution = 1024 × 768) in a darkened room, with text set in black text (#000000) on a light background (#dadada). The experiment was created using the software OpenSeame 3.2 (Mathôt et al., 2012). The participants were seated at a distance of 200 cm from the screen, which was maintained through the use of a chinrest with a forehead strap.

2.4. Procedure

Of all the included stimulus letters, only the aperture letters 'a', 'c', 'e', 'r', 's', 't', and 'f', differed between the font conditions. In the Closed condition, aperture letters had closed apertures, in the Open condition the letters had open apertures, and in the Medium condition, the letter had medium-size apertures. The remaining Non-Aperture letters (i.e., 'd', 'g', 'h', 'k', 'm', 'n', 'o', 'p', 'u', and 'y') were identical between the three font conditions. Non-Aperture letters were selected from the remaining letters of the alphabet to ensure a broad representation of letter shapes.

Participants were asked to report the identity of a single letter in every trial; the letter was shown either in isolation or flanked on both sides by a distractor letter as part of a trigram (Fig. 3). A fixation cross of size 0.63° by 0.63° – at 200 cm – was presented centrally at the onset of a trial for a variable duration of 1.300 ms with a uniformly distributed jitter of ±300 ms. Upon the offset of the fixation cross, the stimulus – consisting of either a single letter or a three-letter string – was presented in the fonts Pyke Closed, Pyke Medium, or Pyke Open for 200 ms, with the target letter being shown at 2° eccentricity either left or right of the fixation cross. The x-height size of the stimulus was determined individually for each participant at the beginning of the experimental session (see 'Staircase Procedure'). Every stimulus letter was shown in each of the three positions in the trigram (i.e., outer-, middle-, and inner-positions) equally often. The stimulus was immediately followed by a backward mask for 500 ms, which consisted of a rectangular noise patch of variable height and width that was equal to the size of the stimulus, such that it covered all letters. Participants were then prompted to report the target letter on the keyboard and to continue to the next trial by pressing the space key. As participants were instructed to maintain fixation on the fixation cross, without moving their gaze towards the stimulus, they could self-report gaze shifts towards the stimulus by reporting any of the numbers on the keyboard instead of the stimulus letter they might have seen; these trials were then discarded. Feedback followed a participant's report in the form of 'Correct', 'Wrong', or a dash, '–', if the participant did not want to report a letter.

In every block, stimulus letters were presented in each of the three fonts 32 times, 16 times as a single letter in isolation and 16 times as part of a trigram, for a total of 96 trials per block.

2.5. Staircase procedure

Task difficulty of reporting the Flanked and Unflanked letters was controlled at the start of the experimental session through the use of two back-to-back accelerated staircase procedures that were adapted from the accelerated stochastic approximation (Kesten, 1958; Treutwein, 1995) and which determined the x-heights separately of first the Unflanked and then the Flanked letters. These staircase procedures employed the same recognition task and trial outline as described in section 2.3, Procedure, with the following exceptions: the target stimulus letter was always presented in isolation in the first staircase procedure and as part of a trigram in the second staircase procedure. Furthermore, stimulus letters were only presented in the font of Pyke Medium. Also, the x-height of the stimulus letters was not constant but determined by Equation (1), included below, meaning that it increased after an incorrect response and decreased after a correct response. The size by which the x-height changed between trials, also referred to as the step size, decreased after a shift in response category (i.e., from correct to incorrect or vice versa). Thus, while the staircase procedure could decrease the step size to make ever finer adjustments to the x-height, it would only do so when those adjustments resulted in a change in the pattern of the participant's response accuracy.

Stimulus letters were presented at an x-height of 0.28° for the first eight trials of the staircase procedures in order to allow participants to familiarise themselves with the experiment. After eight trials, the x-height was given by the equation

$$x_{n+1} = x_n - \frac{c}{m_{shift}}(z_n - 0.70), \quad \text{Equation 1}$$

where n denotes the current trial number – excluding the first eight trials – x_n denotes the x-height of the current trial, x_{n+1} denotes the x-height of the following trial, m_{shift} denotes the number of shifts in response category – excluding any that occurred during the first eight trials (from correct to incorrect or vice versa) – c denotes the initial step size of 0.19°, and z_n is 1 if the response for the current trial is correct and 0 if the response in the current trial is incorrect. The staircase was terminated after 19 reversals, which yielded a response accuracy of 70% (Unflanked x-height average: 0.18° (34 pixels); STD: 0.04° (7.07 pixels); range: 0.14°–0.26° (26–50 pixels); Flanked x-height average: 0.29° (55.61 pixels); STD: 0.08° (16.02 pixels); range: 0.15°–0.47° (29–90 pixels)).

2.6. Results

A three-way repeated-measures ANOVA showed that there was a significant three-way interaction between letter-groups (Non-Apertures and Apertures), Flanker (Flanked and Unflanked), and Aperture conditions (Closed, Medium, and Open), $F(2, 34) = 6.72, p = .003, \omega^2 = 0.011$. We further analysed mean recognition of the Non-Aperture and Aperture letter groups separately using two 2 (Flanker: Flanked vs. Unflanked) by 3 (Aperture condition: Closed, Medium, Open) repeated measures

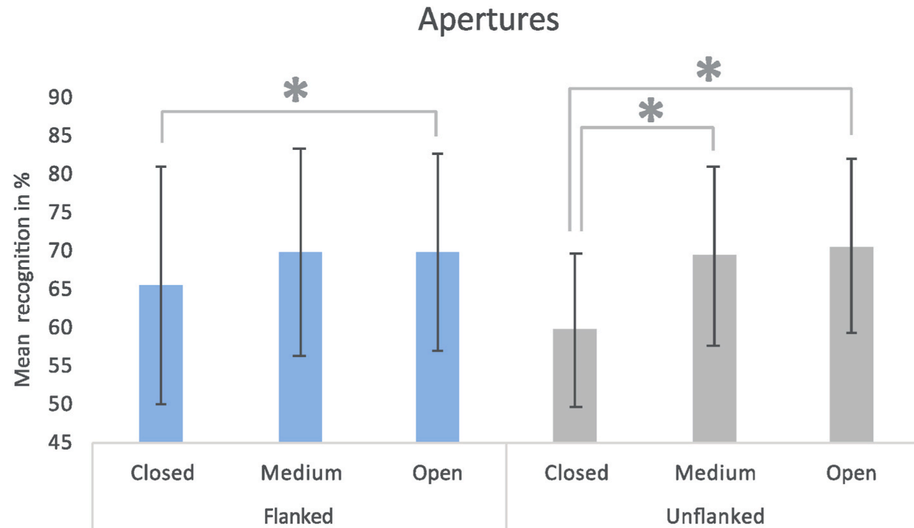

Fig. 4. Mean recognition for Aperture letters (a, c, e, r, s, t, and f), Flanked and Unflanked. Error bars represent standard deviation. Comparisons marked with * were significantly different.

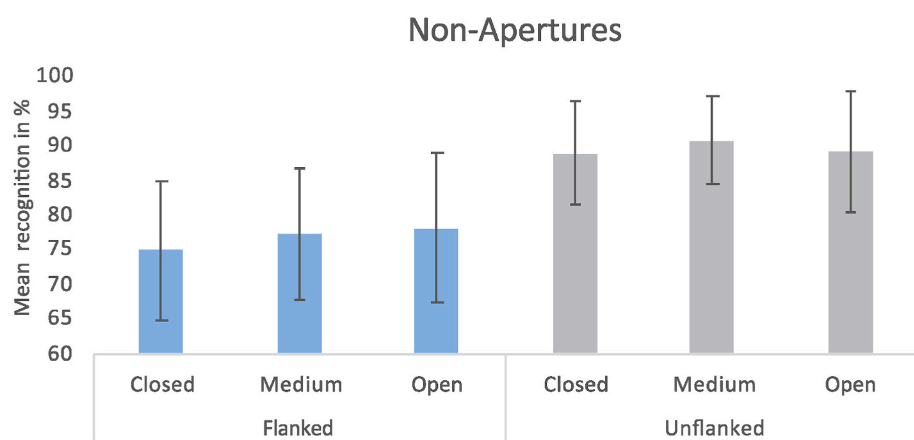

Fig. 5. Mean recognition for identical Non-Aperture letters between fonts (d, g, h, k, m, n, o, p, u, and y) when presented in combination with Closed, Medium and Open apertures. These showed no significant differences. Error bars represent standard deviation.

ANOVAs; the Bonferroni correction was applied for the simple two-way interactions and simple main effects, such that significance level α was set to $.05/2 = .025$.

The simple two-way interaction between Flanker and Aperture condition was significant when the target letter was part of the Aperture letter group, $F(2, 34) = 5.78$, $p = .007$, $\omega^2 = 0.015$ (Fig. 4), but not when the target letter was part of the Non-Aperture letter-group $F(2, 34) = 1.49$, $p = .239$, $\omega^2 = 0.002$ (Fig. 5). For the Non-Aperture letter group, the simple main effect of Flanker was significant, $F(1, 17) = 84.81$, $p < .001$, $\omega^2 = 0.373$, as mean recognition of Flanked letters was significantly lower than that of Unflanked letters, while the simple main effect of Aperture was not, $F(2, 34) = 2.59$, $p = .090$, $\omega^2 = 0.008$. Conversely, for the Aperture letter group, the simple main effect of Flanker was not significant, $F(1, 17) = 0.48$, $p = .500$, $\omega^2 = 0.000$, while the simple main effect of Aperture was significant, $F(2, 34) = 24.81$, $p < .001$, $\omega^2 = 0.088$.

While we, as previously mentioned, found a significant interaction between Flanker and Aperture condition for the Aperture letter group, the simple main effects of Aperture condition were statistically significant for both the Unflanked, $F(2, 34) = 24.85$, $p < .001$, and the Flanked letters, $F(2, 34) = 5.71$, $p = .007$.

Simple planned comparisons, corrected for multiple comparisons using the Bonferroni method - with an adjusted p-value corrected for a family of 6 comparisons - of mean recognition for the Aperture conditions for the Flanked and Unflanked letters showed that mean recognition for Closed Apertures was significantly lower than for Open Apertures in both the Flanked, $t(17) = 3.15$, $p = .035$, $d = 0.74$, and Unflanked Conditions, $t(17) = 5.66$, $p < .001$, $d = 1.34$. Conversely, recognition for Closed Apertures was significantly lower than Medium Apertures in the Unflanked condition, $t(17) = 5.32$, $p < .001$, $d = 1.25$, but not in the Flanked condition, $t(17) = 2.64$, $p = .103$, $d = 0.62$. The difference between Medium Apertures and Open Apertures failed to reach significance for both the Flanked, $t(17) = 0.10$, $p = .999$, $d = 0.002$, and Unflanked conditions, $t(17) = 0.35$, $p = .999$, $d = 0.23$.

3. Discussion

As expected, we found a significant effect of the Closed condition on both Flanked and Unflanked letters compared to the Medium and Open conditions and between Closed and Medium in the Unflanked condition. In light of how small the differences were between the font conditions (Fig. 2), our results support previous work that showed how stroke terminations play a central role in letter recognition (Fiset et al., 2008).

To investigate any possible crowding effects, the target letters were tested both in isolation and when flanked by other letters. Prior studies indicated that the negative effects of peripheral crowding can be

Table 1
Perimetric complexity values of the test characters. This measure is defined as the square of the inside-and-outside perimeter of a character divided by the 'ink' area (Pelli et al., 2006).

Test letters	Pyke Closed	Pyke Medium	Pyke Open
A	65.96	65.40	66.80
C	50.46	46.92	45.06
E	64.25	61.95	60.93
R	54.44	52.69	50.60
S	59.39	58.74	54.59
T	54.30	51.60	51.78
F	66.61	65.13	67.62
Sum	415.41	402.43	397.38
Average	59.34	57.49	56.77

reduced through excessive inter-letter spacing (Perea et al., 2012) and through greater letter differentiation (Bernard et al., 2016). However, we did not find any indication that Closed apertures had a greater negative effect on the crowded Flanked letters than on Unflanked letters, which suggests that the style of the apertures had no influence on the degree of crowding. In fact, only the Unflanked non-crowded test condition showed significant differences between Closed and Medium Aperture conditions, suggesting greater sensitivity to the effects of aperture on Unflanked letters.

Our study replicated earlier findings of open and closed apertures of digits that were presented in a string of three characters at 10° eccentricity (Beier et al., 2018). This indicates that findings reached through experiments with digit recognition can be translated into letter recognition as well. We further replicated findings concerning individual recognition of the lowercase letters 'c' and 'e' from an investigation using different experimental designs and employed an early version of the test font Pyke (Beier and Larson, 2010). While we here looked at the mean recognition of the seven aperture letters collectively, the previous experiment investigated the letters individually.

Our data also followed the expected pattern of letter complexity. The letters of the Closed condition were generally more complex than the letters of the Medium and Open conditions, and the letters of the Medium condition were generally more complex than the letters of the Open conditions (Table 1). Our results aligned with previous findings in demonstrating recognition impairment in the more complex Closed condition (Beier et al., 2018). However, we only found recognition to be impaired in the Medium condition relative to the less complex Open condition when the target letters were Unflanked. Here, it is worth noting that the increase in complexity was greater between Closed and Medium than between Medium and Open.

3.1. Impact and limitations

There is a general consensus within vision science that reading involves parallel operations of low-level identification of letters and their features and high-level lexical processing of word and sentence structures (Coltheart et al., 2001). Between these different operations, letter identification has been shown to be the most significant, accounting for 62% of reading rate, with word recognition accounting for 16% and contextual sentence processing accounting for 22% (Pelli and Tillman, 2007). This demonstrates that letter recognition has a strong effect on reading speed. Based on our methodological approach of quick exposure to stimuli, our findings offer a general contribution to the basis for optimising text settings for glance-like reading. The results further have a direct relevance for any reading situation where letter identification alone is essential, including password setting, wayfinding systems, and road and street signage.

In this experiment, we took great care in isolating the variable of aperture in the selected test letters. This makes it likely that the results can be transferred to many other fonts as well. One caveat of the experiment is that our test fonts had teardrop-shaped stroke endings, which is a common feature in serif fonts. It remains unknown whether the results are dependent on this feature and, thus, whether they might be different if one were to employ font stimuli with more unified letter stroke endings.

4. Conclusion

Though we only found evidence for a performance difference between Medium and Open aperture sizes in the Unflanked letter condition, our findings confirm the often-repeated tenet within the design community that closed apertures hamper recognition. For glance-like reading, where fast letter identification is of great importance, we thus recommend excluding fonts with closed apertures in the letters 'a', 'c', 'e', 'r', 's', 't', and 'f'.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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